Using a Hydrodynamic Lake Model to Predict the Impact of Avalanche Events at Lake Palcacocha, Peru

Rachel Chisolm, Daene McKinney, Marcelo Somos, Ben Hodges
Center for Research in Water Resources, The University of Texas at Austin

Introduction

Tropical glaciers are an essential component of the water resources systems in the mountainous regions where they are located, and a warming climate has resulted in the accelerated retreat of many of these glaciers in recent decades. This research aims to study the flood risk for communities living downstream from glacial lakes that are forming at the termini of glaciers in the Cordillera Blanca mountain range in the Peruvian Andes. As these lakes continue to grow in area and volume, they pose an increasing risk of glacial lake outburst floods (GLOFs) that can be catastrophic to the communities living in the path of these floods. For many decades Lake Palcacocha in the Cordillera Blanca, Peru has posed a threat to citizens living in the watershed below. As new glacial lakes begin to form in the Cordillera Blanca and existing lakes continue to grow, the hazard to the populations living below is continually increasing. A number of GLOFs have occurred in the Andes resulting in great loss of life and property, including a catastrophic GLOF from Lake Palcacocha that destroyed the city of Huaraz and killed 7,000 people in 1941.

GLOFs can be triggered by a failure in the moraine. However, the most common GLOF triggers are landslides, avalanches, or ice calving into the lake; these events result in a large wave that is propagated across the lake and results in water overtopping the moraine. Many of the processes influencing GLOF risk are still poorly understood, and a good understanding of the effect that these processes have on each other is necessary to assess the overall GLOF risk and develop effective mitigation strategies. The glacial watershed system is influenced by many factors, including a changing climate, glacier hydrology and thermodynamics, glacier lake mass balance, lake dynamics, and slope stability. All of these factors contribute to the risk to downstream communities from GLOFs. This research aims to study the GLOF process from start to finish, beginning with the peak of the glacier and ending with the downstream communities. The work presented here focuses on the upper part of the glacial watershed system, from the glacier to the terminal moraine damming the lake, but it is part of a broader effort to assess the overall GLOF risk from Lake Palcacocha (Figure 1). The results from the work presented here will be used as input to a downstream GLOF and risk assessment model.

Scientists and engineers in Peru have several decades of experience managing glacial lakes in the Cordillera Blanca and mitigating GLOF risk, but current lake management practices are based on studies that were performed decades ago and have not been updated to account for changes that have occurred since then and increased water storage in glacial lakes. In addition, significant advances have been made in the field of fluid mechanics and hydrodynamic modeling since the lakes of the Cordillera Blanca were assessed for their vulnerability to GLOF hazards. The application of modern fluid mechanics modeling techniques to high mountain glacial lakes can greatly improve our evaluation of the impact that natural hazards could have on lake dynamics and will subsequently influence the risk assessment for areas downstream. In the work presented here, Lake Palcacocha is used as a case study to investigate the impact of an avalanche event on the lake dynamics and the ensuing flood hydrograph.

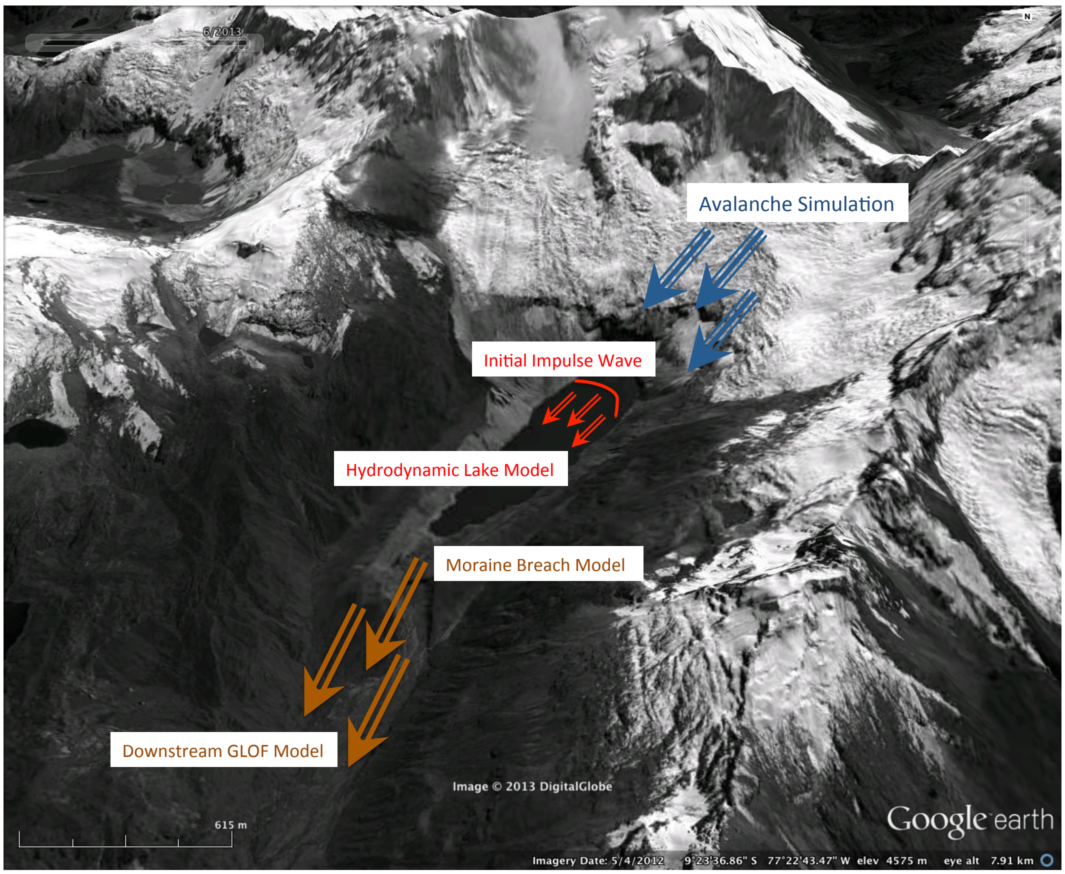

Figure 1: Schematic diagram of the processes to be studied at Lake Palcacocha (image from Google Earth)

Research Objectives

This study aims to assess the impact that an avalanche event from Palcaraju Glacier would have on Lake Palcacocha with the goal of creating a flow hydrograph for a moraine-overtopping event. This flow hydrograph can then be used as an input for a downstream GLOF model. The ultimate goal is to evaluate the effectiveness of the current lake management system and to determine what measures should be undertaken to mitigate GLOF risk for the residents of the Cojup valley and Huaraz.

Empirical equations are used to determine the initial wave characteristics of an impulse wave created by three different avalanche scenarios that represent low, medium and high-risk events. The characteristics of the initial impulse wave are used as inputs to a three-dimensional hydrodynamic model to predict the wave propagation across the lake and the overtopping volume. The results from this model can be used as inputs to a downstream GLOF model to predict the impact from an outburst flood event. Use of a robust three-dimensional hydrodynamic lake model enables more accurate predictions of peak flows during GLOF events and the time scales of these events so that mitigation strategies can be developed that reduce the risk to communities living downstream of hazardous lakes.

A flow hydrograph for each scenario of moraine-overtopping events is produced by accomplishing the following tasks:

- Run avalanche simulations for three risk scenarios
- Determine initial characteristics of the avalanche-generated impulse waves
- Model wave propagation and moraine overtopping with a hydrodynamic lake model

Background

Lake Palcacocha lies at the base of the Palcaraju Glacier and the head of the Cojup River basin (Figure 2). Palcacocha contains approximately 17.3 million m^3 of water and has a maximum depth of 73 m. The average water surface elevation is 4562 m. The steep slope of the Palcaraju glacier directly above Lake Palcacocha and the small amount of freeboard make the lake susceptible to outburst flooding. There have been efforts to control the lake level using siphon tubing, and there is a permanent drainage pipe that maintains the current lake level. Plans to further lower the lake level have been discussed, but as yet nothing has been decided. The results from this hydrodynamic lake level should help determine what lake level should be maintained to keep an adequate freeboard and minimize risk to downstream communities.

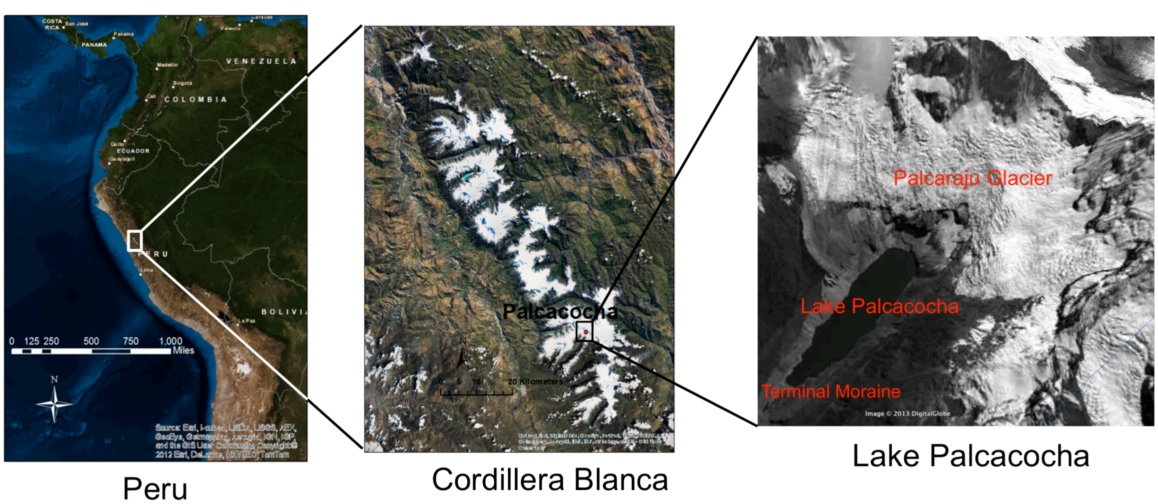

Figure 2: Location of Lake Palcacocha in the Cordillera Blanca, Peru

Avalanche Model

Avalanche simulations were run for three different risk scenarios: low, medium, and high risk. The three risk scenarios are considered with return periods of 100, 30 and 10 years and total avalanche volumes of 3, 1 and 0.5 millions cubic meters respectively. The avalanche module of the RAMMS model, created by WSL in Switzerland, is used to perform the calculations. RAMMS avalanche module solves two-dimensional depth-averaged mass and momentum equations on three-dimensional terrain using both first and second-order finite volume methods (Bartelt *et al.*, 2013). The inputs for the model are: terrain data (DEM), release area and fracture heights and friction parameters. The model computes the velocity of the avalanche, the distance of the run out, the pressure as well as the height of the avalanche front. The result of the avalanche simulations is a set of parameters for each risk scenario. The parameters presented in Table 1 are used to determine the characteristics of the initial impulse wave in the lake.

Table 1: Characteristics of simulated avalanches at Lake Palcacocha for 3 risk scenarios. The avalanche thickness and velocity are given at the point of impact with Lake Palcacocha.

	Avalanche Volume (m^3)	Avalanche Thickness (m)	Avalanche Velocity (m/s)
High Risk	500,000	6	20
Medium Risk	1,000,000	15	32
Low Risk	3,000,000	20	50

Impulse Wave Model

Empirical equations are used to determine the initial characteristics of the avalanche-generated impulse wave according to the method outlined by Heller and Hager (2009). The avalanche characteristics presented in Table 1 are used as inputs to this empirical model along with the dimensions of the lake and the densities of the slide material and water. Inputting the avalanche characteristics into this empirical model results in the wave characteristics for each risk scenario presented in Table 2. These wave properties are used as inputs to the hydrodynamic lake model.

Table 2: Results of impulse wave model for 3 risk scenarios.

	Maximum wave height (m)	Wavelength (m)	Downstream distance to maximum wave height- x_m (m)
High Risk	42	793	392
Medium	21	468	254

Risk			
Low Risk	9	253	147

Hydrodynamic Lake Model

The lake hydrodynamic modeling is being done in Matlab using the Fine Resolution Environmental and Hydrodynamics Model (FREHD), a descendent of the PC2 Matlab model described in Hodges and Rueda (2008) and Ryan and Hodges (2011a,b). The hydrodynamic lake model is being used to model the wave propagation across Lake Palcacocha and the overtopping of the moraine. The model is being run at a 5 m grid resolution with square grid cells. The lake bathymetry data were taken from a bathymetric survey done by the Unidad de Glaciologia y Recursos Hidricos of Peru's National Water Authority (UGRH). The data from the bathymetric survey were extracted to a 5 m grid to be used as input to the hydrodynamic model. The model domain extends downstream of the terminal moraine to the point where the original terminal moraine was destroyed by the 1941 GLOF.

The wave characteristics of the initial impulse wave (Table 2) are reflected in the initial free surface elevation, and the FREHD model simulates the wave propagation from its initial position. A flow hydrograph can be extracted from the results of this hydrodynamic model.

Conclusion

A three-dimensional hydrodynamic lake model will allow for more accurate representation of an outburst flood event than has previously been possible. The work presented here will give a reasonable estimate of the flow hydrograph and total volume for a moraine-overtopping event and will also give an idea of the response time available after an avalanche occurs. After the initial moraine-overtopping, the moraine will likely begin to erode, allowing for complete lake drainage. This event will be modeled through a separate process, but the results of the hydrodynamic lake model will influence the modeling of the ensuing moraine breaching event. While the work presented here will provide the initial flow hydrograph for a GLOF event, it can also be used to determine the time to begin applying the model of the moraine erosion and lake drainage to determine the subsequent flood hydrograph. The two hydrographs can then be combined to be used as inputs to the downstream GLOF model.

The downstream communities that could be affected by a GLOF event are the motivation for this research, and the ultimate goal is to determine what effect a GLOF event may have on these communities. Because each process in the chain of events leading to a GLOF affects the end result, it is important to represent all the physical processes accurately. Improved representation of the upstream processes, such as the avalanche model, impulse wave model, and lake model presented here will better inform the models of downstream processes, such as moraine breaching, GLOF propagation downstream, and risk assessment for affected communities.

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